

Automating the setup and control of the pre-sample charge measurement system at the Lund Ion-beam Analysis Facility

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ABSTRACT

In many IBA applications the aim is to obtain quantitative figures characterising the sample, usually requiring a reliable measurement of the beam current for normalisation. To avoid the drawbacks associated with on-sample and post-sample charge measurement systems a pre-sample measurement system can be used.

In this work an upgrade to the pre-sample charge measurement system at the Lund Ion-beam Analysis Facility is presented, in which a custom built control module based around a Teensy 3.2 micro-controller has been added to the existing system. The new control module allows for remote handling and monitoring of the deflection system, operated via USB connection to a PC running a graphical user interface. Details of the control modules functionality, design and programming are given, as well as the functionality of the user interface. An example of how the new control module can be used for automated calibration of the deflection system is also presented.

1. Introduction

In IBA applications, normalisation to the number of probe particles incident on the target is vital to obtain quantitative figures characterising the sample. Conventionally, charge can be measured directly from the sample or by the use of a post-sample Faraday cup [1]. Such on-sample and post-sample charge measurements are limited in both their applicability and accuracy by sample composition, thickness and conductivity. These limitations are particularly relevant in microbeam analysis where the matrix composition of the sample may vary greatly over the scanned area [2]. Other methods, however, exist which are completely independent of the target [3]. Transmission Faraday cups with a precision of $\sim 1\%$ have been reported [4,5], where charge is measured on a rotating vane which periodically cuts the beam. Alternative methods are the use of a fixed mesh [6] to collect charge, or rotating vanes that backscatter beam particles for measurement [7,8] which also have the possibility of reaching $\sim 1\%$ precision.

In previous work at LIBAF (the Lund Ion-Beam Analysis Facility), a pre-sample charge measurement system was developed, which can be classified as an electric high-voltage chopper [9,10]. Originally implemented in an ion-beam lithography setup, the system continues to be used for PIXE analysis [11], as well as in conjunction with the TIBA (Total Ion-Beam Analysis) chamber for nuclear reaction analysis [12,13]. The precision of the system has been demonstrated to be $\sim 3\%$ [14] and full details of the reproducibility and reliability of charge

measurement have been documented [15].

In this work, a further upgrade to the pre-sample charge measurement system is presented, in which an additional control module based around a Teensy 3.2 micro-controller has been added. This allows for real-time monitoring of the charge collection and adjustment of the deflection voltage when necessary, for example when changing ion or beam energy. All monitoring and adjustment can be performed remotely through serial connection to a desktop PC running a custom built GUI (Graphical User Interface). The system prototype has been tested and is currently in operation on the micro-beamline, in conjunction with the TIBA chamber. A diagram of the experimental setup is shown in Fig. 1, in which components highlighted in green belong only to the upgraded configuration.

2. The manually operated system and motivation for its automation

2.1. The original system

The charge measurement system used on LIBAF's micro-beamline uses a pair of electrostatic deflection plates powered by a PGM (PVM-4210 high-voltage pulse-generator module) to periodically direct the beam into a pre-sample Faraday cup. With no deflection voltage applied the beam is incident in the TIBA chamber at the end of the beamline. The Faraday cup is placed with its centre ~ 5 mm from the centre of the

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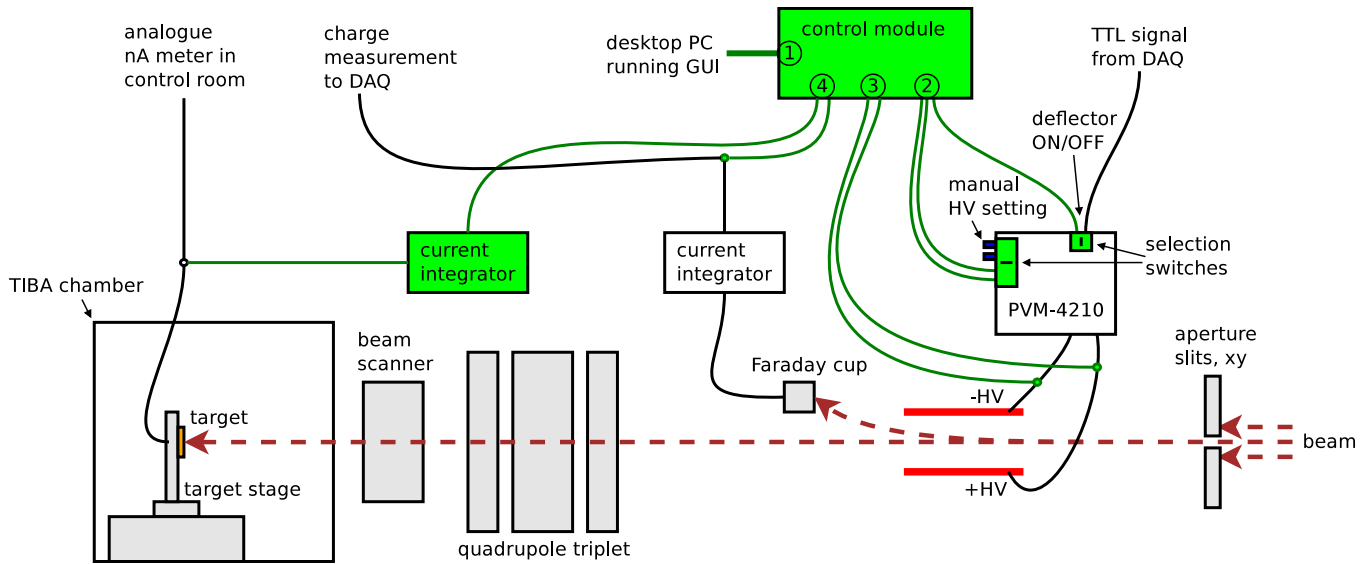


Fig. 1. Diagram of the experimental setup at the end of the micro-beamline at LIBAF (components added in the present work have been highlighted in green). The switches shown on the PVM-4210 pulse generator are used to select whether the system is operated by the new control module or according to the original configuration. The numbering of the control module's connections correspond to those shown in Fig. 3, in which additional details are given. Object slits are not shown, but are placed between the aperture slits and the accelerator. The diagram is not to scale.

beamline, at a distance of ~ 7 cm from the end of the deflection plates which have a length of ~ 50 cm and have a separation of ~ 1 cm. The maximum potential that can be applied across the plates by the PGM is ~ 1900 V.

The cup itself is constructed from a flat carbon block ~ 12 mm across, with a grounded stainless steel guard ring mounted in front of it. The guard ring leaves an exposed section of the carbon ~ 5 mm in diameter, this being the active area of the cup. No bias electrode is used. This construction results in a system that cannot provide absolute charge measurement due to electron escape, but is still suitable for relative charge measurements that can be used in conjunction with standard samples when performing analysis.

The beam is collimated down to a diameter < 1 mm before the deflection system using two pairs of slits: the object and the aperture. The deflector is mounted ~ 5 cm after the aperture slits which are mounted ~ 10 m after the object slits. It is essential that the deflection system is mounted after the last pair of slits, firstly to ensure a spot size in the cup much less than its active area, and secondly to ensure that the charge measurement is performed on the same cut of the beam used for analysis. Focusing magnets and beam scanning system are located after the deflector, ensuring that they cannot influence the charge measurement.

A current integrator, produced by Gammadata Instrument AB Sweden, is used to measure the charge collected in the Faraday cup. The current integrator can be set to produce output pulses at a rate of either one per 10 pC or one per 100 pC, with a maximum output frequency of 10 kHz. This results in a measurement range of between 10 pA and 1 μ A which is sufficient for the geological samples studied at this beamline, these tolerating relatively high beam currents with analysis usually being performed at between 1 nA and 5 nA. An analogue nA-metre is used to measure current on the target holder in the TIBA chamber if necessary.

Triggering of the PGM is controlled by the DAQ (data-acquisition system) via a TTL signal. The potential applied to the deflection plates is controlled by a pair of potentiometers on the PGM itself, no readout of the potential is available. Reading of the Faraday cups current integrator is performed by the DAQ via a fast-scalar module. Under standard operation the deflector is activated to make a charge measurement for one second, for every 10 s the beam is incident on the sample being analysed.

2.2. Scope for improvement

The deflection of an ion when passing between a pair of charged parallel plates can be easily calculated [16]. The deflection angle being given by:

$$\theta = \tan^{-1}(lVQ/2dE), \quad (1)$$

in which l is the length of the deflector plates, V is the potential between the plates, Q is the charge state of the ion, d is the separation of the plates and E is the energy of the beam. For the full deflection system, the result of Eq. 1 can be used to determine the position of the beam at given distance for a given plate potential using:

$$x = \tan(\theta + \theta_0)(f + l) + x_0, \quad (2)$$

where θ_0 is the angle of the beam as it enters the deflector, f is the length of the flight path from the deflector exit to the measurement point and x_0 is the offset in the beam position when entering the deflector. The results of such a calculation, for three different beam energies, are presented in Fig. 2

Although Eq. (2) provides a good approximation to the deflection of a given beam, which maybe sufficient in many situations, relying on a such calculation can be problematic. Firstly, Eqs. 1 and 2 do not take fringe fields at the entry and exit of the deflector into account and these second order effects must be obtained by simulation. Secondly, Eq. 1 assumes a mono-energetic beam which is not, in practice, accurate and will therefore not account for spreading of the beam after deflection. Thirdly, precise knowledge of the deflector geometry is required which may not be available in older setups where documentation is lacking and can only be obtained by complete deconstruction and reconstruction of the apparatus. Finally, values for θ_0 and x_0 must be known: these can be very difficult to obtain and will change if beamline components are realigned. It is therefore important that for such a calculation to be relied upon it must be validated by measurement.

During experiment, the operation of the deflection system and the reading of charge deposited in the Faraday cup is fully controlled by the DAQ. Calibration of the system however, has been completely manual until this time. Such calibration being required any time beam parameters are changed. Manual calibration is a time intensive process, requiring repeated adjustment and measurement of the potential on the deflector plates while repeatedly measuring the current in the Faraday

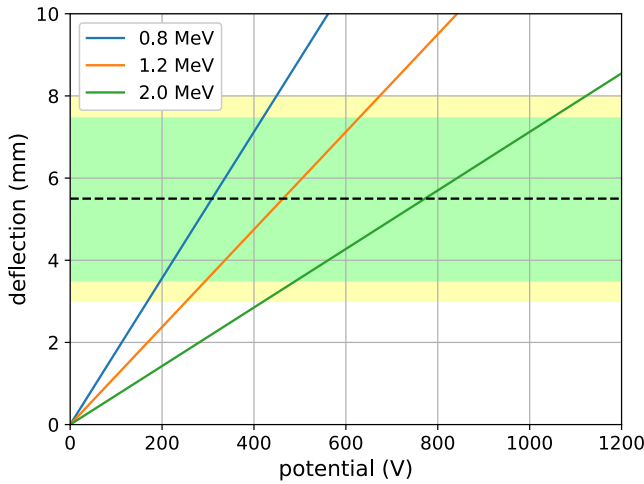


Fig. 2. Calculated deflection of protons, at three different energies, as a function of deflection potential using Eq. 2. Values for θ_0 and x_0 have been taken to be zero. The geometry used in the calculation is that for the deflector setup currently used on the TIBA beamline at LIBAF. The shaded regions indicate the range of deflection that will leave the beam incident in the Faraday cup: yellow being partly incident, green being fully incident, under the assumption of a 1 mm spot size.

cup with an analogue nA-metre. When performing measurements where the energy of the beam must be scanned, the procedure becomes impractical. When using a deuterium beam, manual setup is limited due to the risk of irradiation to the user. This means the deflector must be setup using a proton beam and the ion source then changed with the assumption that the deflection setting will remain adequate.

3. The new control module and its integration

3.1. Overview

The system upgrade involves the modification of the PGM for remote operation using a Teensy 3.2 micro-controller. The micro-controller is mounted on a separate board with several additional components to facilitate this control and provide the user with a number of data parameters for monitoring the deflectors operation. The new controller board is illustrated schematically in Fig. 3.

The majority of the programmed functionality of the system resides on the micro-controller, implemented in C++. The GUI is implemented in such a way that it tells the controller which function to perform and receives, displays and logs data returned to it in 16 byte transmissions. The front-end of the GUI was designed using Qt5 and the back-end is implemented in Python3. An annotated screen-shot of the GUI is presented in Fig. 4.

In terms of hardware capability, the control module offers:

- a pair of HV-metres for live measurement of the potential applied to the deflector plates;
- two frequency to digital converters for monitoring current integrator outputs;
- a pair of analogue outputs for setting the potential applied to the deflector plates by the PGM;
- a TTL output for controlling PGM triggering;
- remote control via USB connection.

Each of these is discussed in turn.

3.2. Digital HV-metres

Each HV-metre is constructed of a passive potential divider and

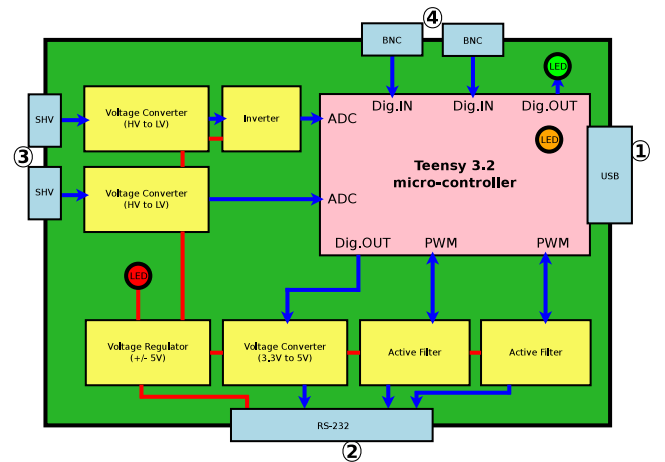


Fig. 3. Schematic of the new control module. Board connections are: (1) connection to PC running GUI, supplying both communication and power to the micro-controller; (2) connection to the PVM-4210 pulse generator module, receiving power for circuit components and outputting HV control; (3) connection to deflector plates for measuring HV; (4) TTL input from current integrators. Connector numbering corresponds to that shown on the control module in Fig. 1.

LM714 op-amp(s) which together produce gains ≈ 0.0025 and -0.0025 for the positive and negative voltage terminals respectively. This puts the maximum voltage that can be applied to the deflector plates (± 950 V) within the 0–3.3 V range of the micro-controller's 13 bit ADCs. The resulting resolution of the HV-metres is ~ 0.12 V.

Due to the high impedance of the HV-metres, they can be permanently connected to the deflection plates without influencing their operation. The inputs are also low-pass filtered for noise suppression.

3.3. Digital nA-metres

Charge measurement is performed by directly reading the pulsed output of the current integrator module(s) using the ADC channels of the micro-controller. The micro-controller does this by counting the rising edges of the pulses received. Two ADC channels are reserved for this purpose meaning that, in addition to the connection of the current integrator for the Faraday cup, a second current integrator can be connected for reading charge collected on the sample holder or in the Faraday cup in the chamber. The resolution of the system is limited by the current integrator, this being 10 pC.

3.4. HV controllers

Control of the potential applied to the deflection plates is achieved by replacing the analogue potentiometers of the PGM with direct voltage control using 12 bit PWM (pulse-width modulation) outputs from the Teensy 3.2. The PWM signals are low-pass filtered using Chebyshev and Butterworth configurations with an output ripple of $> 0.01\%$. This results in a control of the potential between the deflector of 0.5 V over the entire 1900 V range.

To add redundancy into the system the original potentiometers have been left in place in the PGM, but connected through one side of a multiple-pole ON-ON switch. Connection to the digital potentiometers is made through the other side of the switch. In this way, the original functionality of the PGM can be returned without the need for rewiring.

3.5. Triggering the PGM

A level shifter, built from a LM714 op-amp, is used to convert one of the 3.3 V digital outputs from the micro-controller to 5 V TTL. As the DAQ must have control of the triggering of the PGM during



Fig. 4. An annotated screen-shot of the new GUI control panel, designed using Qt5 and Python3.

experimental operation, an ON-ON switch mounted on the PGM is used to select which control signal is passed.

3.6. Remote control

Five controller functions are selectable by user input to the GUI, in addition to a default function. The default operation is to collect the voltage and charge measurements and return these to the GUI. User selected functions are as follows:

1. terminate the USB connection;
2. adjust the potential on deflector plates;
3. switch ON/OFF/cycle deflection;
4. run/cancel an automated voltage sweep;
5. pause/unpause data transmission to the GUI.

Out of the five functions listed, 2 and 3 replicate the control of the system before the upgrade but with the advantage of remote operation. Function 4 however, fully automates the calibration of the deflector system by stepping the potential applied to the plates through a user defined voltage range while cycling the deflection on and off. This is discussed in more detail in Section 4.

4. Example of application – Auto-calibration results

The ability to automatically calibrate the deflection system is one of the most powerful features of the new control module. By clicking the ‘Run Voltage Sweep’ button on the GUI (see Fig. 4), the control module systematically increments the potential between the deflector plates in steps of ~ 20 V and, at each step, measures the charge collected in the Faraday cup. To ensure that any long time-scale instability in the beam is accounted for, a reference charge measurement is also made in the chamber at each voltage step by cycling the deflector on and off. The standard duration of each full cycle is 2 s, 1 s of deflection and 1 s without, although this can be redefined by the user from the GUI. All data is logged in the GUI in real-time and is saved once the sweep is completed. To scan the entire voltage range of the PGM takes ~ 80 s, although the user can define start and stop voltages for the scan to reduce this time if an approximate range is known in advance.

Fig. 5 presents the results of three voltage sweeps using proton beams of 0.8 MeV, 1.2 MeV and 2.0 MeV and a current of ~ 3 nA. The beam was aligned prior to calibration using a fluorescent plate in the target position (see Fig. 1). The fluorescent plate was then replaced by a copper plate to give a reliable charge measurement in the chamber. The magnitude of the potentials on each deflector plate were kept equal at

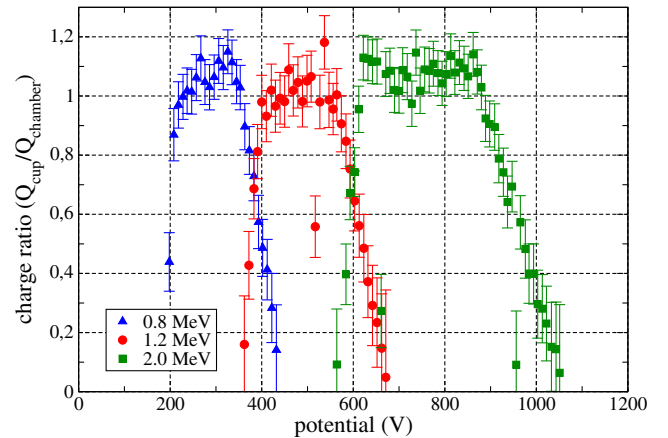


Fig. 5. Deflector calibration plots generated by the new setup. The charge ratio between the Faraday cup and the TIBA chamber can be seen to plateau over a range of potentials for each beam energy, indicating that the beam is incident in the Faraday cup. Uncertainties are derived from the counting statistics on each charge measurement, additional uncertainty originating from instability of the beam during measurement is not accounted for.

each step of the sweep. Plotted are the ratios of the two charge measurements, measurement in the cup and measurement in the chamber, against the total potential between the deflector plates. The range of acceptable values for the deflector potential are those that form the plateau in each data set.

It is important to note that the charge measurements used in the ratios plotted are not absolute and indeed can not be for the reasons discussed in Section 2.1. This is evident in Fig. 5 as the mean height of the plateau is > 1.0 in all three cases and indicates that electron escape is even higher from the Faraday cup than it is from the copper plate in the chamber. The variation in the height of the plateau between each of the three measurements is possibly explained by the repositioning of the copper plate, with surface effects on the copper resulting in variation in electron escape. The variation of the height of the plateau within each measurement, particularly those at 0.8 MeV and 1.2 MeV, is possibly explained by similar surface effects on the Faraday cup itself. Both of these hypotheses would require further investigation to be confirmed. For the purposes of calibrating the deflection system, the exact charge ratio obtained is not important, only the location of the plateau. Further to this, the deviation of the mean from 1.0 is not a reflection of the uncertainty in the system as such systematics are removed in sample measurement through normalisation to standards. The

statistical uncertainties indicated in Fig. 5 are also large compared to those obtained during sample measurement. The measurement time used to obtain the calibration plots presented here is only 2 s per point, whereas for a true sample measurement the time would be on the order of 1000 times this.

By comparing the results in Fig. 5 with the calculated values for deflection presented in Fig. 2, agreement can be seen across only about 50% of the potential range for each beam energy. It can be seen that in these cases, choosing potentials predicted by Eq. 2 to centre the beam in the cup would be sufficient for charge collection, but would not truly centre the beam in the cup. It is easy to see that subtle realignment of beamline components, the use of a larger beam spot or the use of a smaller cup could all cause the calculated potentials to fail to result in complete charge collection. This would be detrimental, even to the relative charge measurements performed for sample analysis on this beamline. The calibration system however, is insensitive to these factors and also provides additional information. The spread of the beam at higher deflection potentials can, for example, be read directly from Fig. 5, information which would require detailed knowledge of the beam properties combined with beam transport simulation to otherwise obtain.

5. Summary

A new controller for the pre-sample charge measurement system used at LIBAF has been developed and the prototype is operation with the TIBA chamber on the micro-beamline. The controller:

- is fully integrable with the existing data acquisition system;
- can be remotely operated;
- provides real-time monitoring and logging of deflector potential and charge collection;
- and allows for automated calibration of deflector potential.

Declarations of interest

None.

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